Downlink Interference Alignment with Multi-User and Multi-Beam Diversity for Fog RANs

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***Abstract*—In this paper, we propose a novel opportunistic downlink interference alignment with a beam selection (ODIA-BS) technique for fog-radio access networks (F-RANs). With joint transmit and receive beamforming strategies, inter-cell interference is effectively suppressed and intra-cell interference is perfectly eliminated. The performance in terms of sum-rate is improved by selecting a proper transmit beam through F-RAN with low signaling overheads. We also develop a spectrally-efficient ODIA-BS (SE-ODIA-BS) technique to further improve the sum-rate performance, where the scheduler at remote radio head selects users with the most orthogonal effective channel vector to each other. Through extensive computer simulations, it is shown that the sum-rate of the proposed ODIA-BS and SE-OIDA-BS techniques outperform other conventional schemes in the F-RAN environment.**

***Index Terms*—Beam selection, coordinated beamforming, fog-radio access network (F-RAN), opportunistic downlink interference alignment (ODIA), user scheduling.**

I. INTRODUCTION

With the advent of 5G cellular networks, fog-radio access networks (F-RANs) have emerged as a popoular technology to overcome disadvantages of clould-RANs, such as decrease in spectral/energy efficiencies, and delay performance resulted from practical fronthaul limits [1]. On the flip side, as the total number of connected devices becomes more than tens of billions, interferences are considered to be one of dominant limiting factors in the performance of 5G networks. To be specific, cellular networks are operated in the interference-limited regime. Consequently, the performance of cellular networks can be considerably improved if inter-cell interference as well as intra-cell interference are properly managed. In F-RAN, a large amount of storage, signal processing, control, and management are performed at the edge of a network in a distributed manner. Generally, a fog-access point (F-AP) can coordinate multiple radio remote heads (RRHs) in order to manage the interference with low signaling overheads. In [2], the coordinated precoding technique, which refers to joint processing of coordinated multipoint (CoMP), with RRH clustering algorithms and several scheduling algorithms were presented to suppress interference in the F-RAN. In [3], an interference-aware resource allocation scheme was proposed based on a non-cooperative game, and it outperformed other schemes in terms of achievable data rate.

To fundamentally solve the interference problem, the concept of interference alignment (IA) was introduced in [4], where multiple communication pairs exist in the network. Based on IA framework, opportunistic interference alignment (OIA) framework was proposed in [5], [6]. The main idea of OIA is to combine user scheduling with the classical IA technique in order to take advantage of multi-user diversity gain. For the OIA framework, a variety of transmit/receive beamforming techniques and user scheduling algorithms were proposed, and the effect of multi-user as well as the multiplexing gain were investigated in [7]–[10]. More specifically, [9], [10] studied an opportunistic downlink interference alignment (ODIA) framework for multi-cell and multi-user multiple-input multiple-output (MIMO) networks. In [9], the optimal way of using multi-user diversity for single-input multiple-output (SIMO) downlink networks was investigated, and the relation between degree of freedom (DoF) and interference was derived as the number of users in a cell. Subsequently, Lee *et al.* [9] extended the study to the MIMO downlink networks by an orthonormal random beamforming strategy. In [10], the ODIA framework was studied for interference-limited cellular downlink networks, and the user scaling condition, in which represents a parameter as the minimum number of users required to achieve a target DoF, was fundamentally reduced by coordinated beamforming strategy. Furthermore, limited feedback methods for ODIA was proposed while the same user scaling condition as the system with perfect channel state information. The author of [10] showed the optimal multi-user diversity can be achieved without a dramatically changed user scaling condition by adopting the semi-orthogonal user selection algorithm introduced in [11].

In this paper, we propose an ODIA with beam selection (ODIA-BS) scheme for an F-RAN which consists of an F-AP and RRHs. In the proposed ODIA-BS scheme, the inter-cell interference as well as the intra-cell interference can be effectively managed by the coordinated beamforming strategy at each RRH and each user. Specifically, the intra-cell interference can be eliminated by the first transmit user-specific beamforming strategy based on linear zero-forcing (ZF) filtering. The intra-cell interference is perfectly removed under the condition that the number of selected users in a RRH is less than or equals to the number of antennas of each RRH. For the second transmit beamforming strategy, multiple random beamforming matrices are constructed in a pseudo-random manner, and one of them is used to reduce the

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inter-cell interference from neighboring RRHs. In addition, we design the receive beamforming vectors in order to mitigate the inter-cell interference at each user by minimizing the interference from other RRHs only with local channel state information (CSI). In the ODIA-BS scheme, each RRH selects the least interfered users from neighboring RRHs. Furthermore, we develop a spectrally efficient ODIA-BS (SE-ODIA-BS) scheme which improves the sum rate performance by scheduling users with the greatest gain by orthogonal effective channel vectors from those of previously selected users.

II. SYSTEM AND CHANNEL MODELS

We consider a F-RAN, in which each of K RRHs having M antennas and each of N users with L antennas as shown in Fig. 1. Each RRH is connected to the F-AP by wired link. Hereafter, the RRHs are also referred to as cells interchangeably. At each cell, $|\mathcal{D}|$ reference beam matrices are generated in a pseudo random manner. The number of selected users in each cell is denoted by S $(\leq M)$, and each selected user transmits a single spatial stream to their associated RRH. In addition, we assume $L \leq (K-1)S+1$ in order to completely eliminate the inter-cell interference by ZF based transmit beamforming strategy. The channel matrix from the k-th RRH to the j-th user in the i-th cell is denoted by $\mathbf{H}_k^{[i,j]} \in \mathbb{C}^{L\times M}$, where $j \in \mathcal{N} \triangleq \{1,\ldots,N\}$ and $i,k \in \mathcal{K} \triangleq \{1,\ldots,K\}$. Each element of $\mathbf{H}_k^{[i,j]}$ is assumed to be independent and identically distributed (i.i.d.) according to $\mathcal{CN}(0,1)$. Furthermore, channel coefficients are constant during one transmission block and vary for every transmission block. Each user can easily estimate the channel coefficients using pilot signals sent from all RRHs by the channel reciprocity of time-division duplexing (TDD) systems.

III. PROPOSED ODIA-BS

In this section, we explain the proposed ODIA-BS scheme for multi-user F-RAN, and then we derive the achievable data rate of users. The overall procedure of the ODIA-BS scheme consists of following four steps: initialization, receive beamforming design and scheduling metric feedback, user scheduling and transmit beamforming construction, and downlink data transmission.

A. Overall Procedure

1) *Initialization*

At each RRH, the reference beamforming matrices are generated by $\mathbf{P}_i^{[d]} = \left[\mathbf{p}_{1,i}^{[d]}, \cdots, \mathbf{p}_{S,i}^{[d]}\right]$, where $\mathbf{p}_{s,i}^{[d]} \in \mathbb{C}^{M\times 1}$ for $s = 1,\cdots,S$, $i \in \mathcal{K}$, and $d \in \mathcal{D}$. The column vector $\mathbf{p}_{s,i}^{[d]}$ denotes an orthonormal basis of an S-dimensional subspace of $\mathbb{C}^{M\times M}$. We assume that $\mathbf{P}_i^{[d]}$ is generated in a pseudo-random manner, and thus there is no need to broadcast the reference beamforming matrices from each RRH to each user. The one of simple ways to construct the reference beamforming matrix is extracting S column vectors from the left or right singular vectors after singular value decomposition of the randomly generated $M \times M$ matrix. The roles of $\mathbf{P}_i^{[d]}$ shall be explained in Section 3. The CSI between multiple RRHs and each user can be easily obtained from the CSI-reference signal (RS) from the RRHs at each user. In this paper, we assume that the perfect CSI can be used at the users.

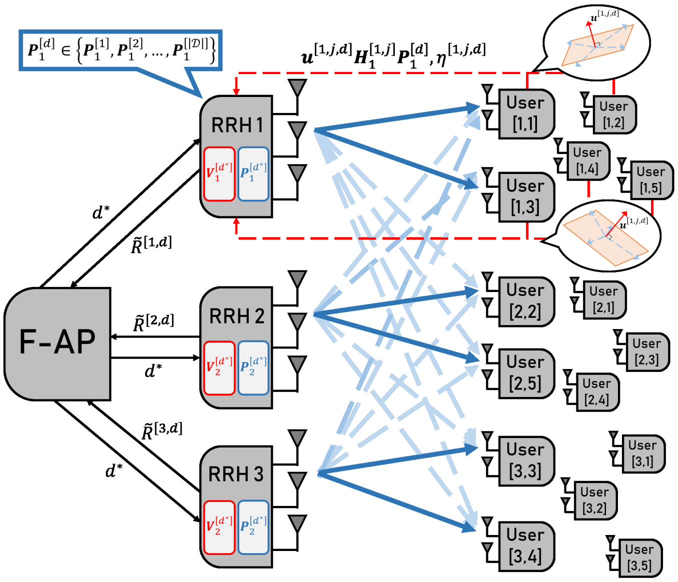

Fig. 1. Proposed system model, where $K = 3$, $M = 3$, $S = 2$, $L = 2$, and $N = 5$.

2) *Receive Beamforming Design and Scheduling Metric Feedback*

Each user designs the receive beamforming vector based on the CSI and the reference beamforming matrices of neighboring cells. Let $\mathbf{u}^{[i,j,d]} \in \mathbb{C}^{M\times 1}$ denote the unit-norm receive beamforming vector for the j-th user in the i-th RRH, where the d-th reference beamforming matrix is exploited. Then, with $\mathbf{P}_i^{[d]}$ and $\mathbf{H}_k^{[i,j]}$, we can define the following quantity as the scheduling metric at each user:

$$\eta^{[i,j,d]} = \sum_{k=1,k\neq i}^{K} \left\| \mathbf{u}^{[i,j,d]^H} \mathbf{H}_k^{[i,j]} \mathbf{P}_k^{[d]} \right\|^2, \tag{1}$$

where $i \in \mathcal{K}, j \in \mathcal{N}$, and $d \in \mathcal{D}$. It is worth noting that even though $\eta^{[i,j,d]}$ can be regarded as the inter-cell interference at the j-th user in the i-th RRH, where the d-th reference beamforming matrix is used, it is not the exact amount of inter-cell interferences because the second transmit beamforming matrix is not considered. From (1), the user calculates the receive beamforming vector as follows:

$$\begin{aligned}\mathbf{u}^{[i,j,d]} &= \arg\min_{\mathbf{u}} \eta^{[i,j,d]} \\ &= \arg\min_{\mathbf{u}} \sum_{k=1,k\neq i}^{K} \left\| \mathbf{u}^H \mathbf{H}_k^{[i,j]} \mathbf{P}_k^{[d]} \right\|^2 . \end{aligned} \tag{2}$$

In the ODIA-BS scheme, the inter-cell interference can be reduced by selecting the receive beamforming vector which minimizes $\eta^{[i,j,d]}$.

For user scheduling and construction of transmit beamforming matrix, the user j in the RRH i should feed back the values $\eta^{[i,j,d]}$ and the effective channel vectors $\mathbf{f}_i^{[i,j,d]} = \left(\mathbf{u}^{[i,j,d]H}\mathbf{H}_i^{[i,j]}\mathbf{P}_i^{[d]}\right)^H$ for all $d \in \mathcal{D}$.

3) *User Scheduling, Beam Selection, and Transmit Beamforming Construction*
After every RRH received all feedback data from users, each RRH proceeds temporal user scheduling for each beam matrix as follows:

- Step 1: Initialize the set of users:
$$\mathcal{N}_1 = \mathcal{N} = \{1, \cdots, N\}, \; s = 1 \tag{3}$$
- Step 2: For each $d \in \mathcal{D}$, the s-th scheduled user $j_s^{[i,d]}$ is selected as
$$j_s^{[i,d]} = \arg\min_j \eta^{[i,j,d]} \tag{4}$$
where $j \in \mathcal{N}_s$.
- Step 3: Update the set of candidate users:
$$\mathcal{N}_{s+1} = \left\{ j : j \in \mathcal{N}_s, j \neq j_s^{[i,d]} \right\}, s = s+1. \tag{5}$$
Repeat Step 2 to Step 3 until $s = S$.

With the d-th beam matrix, the i-th RRH temporarily calculates an orthogonal projection vector of the s-th scheduled user $\mathbf{b}^{[i,j_s^{[i,d]},d]}$ as follows:

$$\begin{aligned}\mathbf{b}^{[i,j_s^{[i,d]},d]} =& \mathbf{f}_i^{[i,j_s^{[i,d]},d]} \\ &- \sum_{s'=1}^{s-1} \frac{\mathbf{b}^{[i,j_{s'}^{[i,d]},d]}\mathbf{f}_i^{[i,j_{s'}^{[i,d]},d]}}{\left\|\mathbf{b}^{[i,j_{s'}^{[i,d]},d]}\right\|^2}\mathbf{b}^{[i,j_{s'}^{[i,d]},d]}. \end{aligned} \tag{6}$$

By (6), now the i-th RRH could calculate the beam matrix selection metric of the d-th beam matrix as follows:

$$\widetilde{R}^{[i,d]} = \sum_{s'=1}^{S} \log_2 \left(1 + \frac{\left\|\mathbf{b}^{[i,j_{s'}^{[i,d]},d]}\right\|^2}{\frac{S}{SNR} + \eta^{[i,j_{s'}^{[i,d]},d]}} \right), \tag{7}$$

where SNR denotes the signal-to-noise ratio. Since $\left\|\mathbf{b}_{s'}^{[i,d]}\right\|^2$ and $\eta^{[i,j_{s'}^{[i,d]},d]}$ are not actual value of beamforming gain and inter-cell interference, (7) is not actual sum rate value of the i-th RRH where the d-th beam matrix is used. However, it can be regarded as the sum rate of each RRH. For all d, each RRH sends calculated $\widetilde{R}^{[i,d]}$ value to F-AP. With all received $\widetilde{R}^{[i,d]}$ values, F-AP selects the index of chosen reference beamforming matrix d^* with (8), and indicates d^* to all RRHs.

$$d^* = \arg\max_d \sum_{i=1}^{K} \widetilde{R}^{[i,d]}. \tag{8}$$

Note that there is no huge burden to notice d^* information to all RRHs, because d^* is non-negative integer value.
After receiving d^* at each RRH, the RRH can determine users to be scheduled. From the effective channel vectors of selected users d^*, each RRH constructs the first transmit beamforming matrix which conducts the ZF filtering to perfectly eliminate the intra-cell interference under $S \leq M$. For d^*, the first transmit beamforming matrix $\mathbf{V}_i^{[d^*]} \in \mathbb{C}^{S \times S}$ is written as

$$\begin{aligned}\mathbf{V}_i^{[d^*]} &= \left[\mathbf{v}^{[i,1,d^*]}, \cdots, \mathbf{v}^{[i,S,d^*]}\right] \\ &= \begin{pmatrix} -\mathbf{f}_i^{[i,1,d^*]H}- \\ -\mathbf{f}_i^{[i,2,d^*]H}- \\ \vdots \\ -\mathbf{f}_i^{[i,S,d^*]H}- \end{pmatrix}^{-1} \\ &\cdot \begin{pmatrix} \sqrt{\gamma^{[i,1,d^*]}} & 0 & \cdots & 0 \\ 0 & \sqrt{\gamma^{[i,2,d^*]}} & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & \sqrt{\gamma^{[i,S,d^*]}} \end{pmatrix}, \end{aligned} \tag{9}$$

where $\gamma^{[i,s,d^*]} = \frac{1}{\left\|\mathbf{P}_{i,d^*}\mathbf{v}^{[i,s,d^*]}\right\|}$.

4) *Downlink Data Transmission*
After performing user scheduling and construction of transmit beamforming, each RRH transmits the downlink data to scheduled users. The received signal vector at the j-th user in the i-th cell is written as

$$\begin{aligned}\mathbf{y}^{[i,j]} =& \mathbf{H}_i^{[i,j]}\mathbf{P}_i^{[d^*]}\mathbf{V}_i^{[d^*]}\mathbf{x}_i \\ &+ \sum_{k=1,k\neq i}^{K} \mathbf{H}_k^{[i,j]}\mathbf{P}_k^{[d^*]}\mathbf{V}_k^{[d^*]}\mathbf{x}_k + \mathbf{z}^{[i,j]} \\ =& \underbrace{\mathbf{H}_i^{[i,j]}\mathbf{P}_i^{[d^*]}\mathbf{v}^{[i,j,d^*]}x^{[i,j]}}_{\text{desired signal}} \\ &+ \underbrace{\sum_{s=1,s\neq j}^{S} \mathbf{H}_i^{[i,j]}\mathbf{P}_i^{[d^*]}\mathbf{v}^{[i,s,d^*]}x^{[i,s]}}_{\text{intra-cell interference}} \\ &+ \underbrace{\sum_{k=1,k\neq i}^{K} \mathbf{H}_k^{[i,j]}\mathbf{P}_k^{[d^*]}\mathbf{V}_k^{[d^*]}\mathbf{x}_k}_{\text{inter-cell interference}} + \mathbf{z}^{[i,j]}. \end{aligned} \tag{10}$$

The received signal after the receive beamforming, which is denoted by $\widehat{y}^{[i,j]} = \mathbf{u}^{[i,j,d^*]H}\mathbf{y}^{[i,j]}$, is given by

$$\begin{aligned}\widehat{y}^{[i,j]} =& \mathbf{f}_i^{[i,j,d^*]}\mathbf{v}^{[i,j,d^*]}x^{[i,j]} \\ &+ \mathbf{f}_i^{[i,j,d^*]H} \sum_{s=1,s\neq j}^{S} \mathbf{v}^{[i,s,d^*]}x^{[i,s]} \\ &+ \sum_{k=1,k\neq i}^{K} \mathbf{f}_k^{[i,j,d^*]H}\mathbf{V}_k^{[d^*]}\mathbf{x}_k + \mathbf{u}^{[i,j,d^*]H}\mathbf{z}^{[i,j]}. \end{aligned} \tag{11}$$

Based on (11), the achievable data rate of the j-th user in the i-th cell can be calculated as

$$R^{[i,j]} = \log_2\left(1 + SINR^{[i,j]}\right)$$
$$= \log_2\left(1 + \frac{\gamma^{[i,j,d^*]}|x^{[i,j]}|^2}{|\mathbf{u}^{[i,j,d^*]H}\mathbf{z}^{[i,j]}|^2 + I^{[i,j]}}\right), \quad (12)$$

where $I^{[i,j]} = \sum_{k=1,k\neq i}^{K} |\mathbf{f}_k^{[i,j]H}\mathbf{V}_k^{[d^*]}\mathbf{x}_k|^2$.

B. Spectrally Efficient ODIA (SE-ODIA) with BS

In this subsection, we describe the SE-ODIA-BS scheme, which improves the achievable sum rate performance by selecting proper users related with channel gain. In the ODIA-BS, users with the smallest amount of interference from inter-cells are selected, whereas the SE-ODIA-BS scheme selects users with the greatest orthogonal effective channel gain from users that fulfill η_I constraint. Most of the overall procedure of SE-ODIA-BS follows that of the ODIA-BS described in III-A except user scheduling. In user scheduling procedure, the SE-ODIA-BS starts with Step 2 after initialization, which is the same with the ODIA-BS. Moreover, the user scheduling procedure of the SE-ODIA-BS is described as follows:

- Step 2: the i-th RRH calculates an orthogonal projection vector $\mathbf{b}^{[i,j,d]}$ of each user in the i-th cell by (6). Remarking (6), for $s = 1$, $\mathbf{b}^{[i,j,d]} = \mathbf{f}_i^{[i,j,d]}$ and for $s > 1$, it considers the orthogonal beam of scheduled users.
- Step 3: For each $d \in \mathcal{D}$, the s-th scheduled user $j_s^{[i,d]}$ is selected as
$$j_s^{[i,d]} = \arg\max_j \left\|\mathbf{b}^{[i,j,d]}\right\|^2, \quad (13)$$
with the constraint
$$\eta^{[i,j_s^{[i,d]},d]} \leq \eta_I, \quad (14)$$
where η_I denotes the pre-defined threshold value.
- Step 4: Update the set of candidate users:
$$\mathcal{N}_{s+1} = \left\{j : j \in \mathcal{N}_s, j \neq j_s^{[i,d]}\right\}, s = s + 1. \quad (15)$$
Repeat Step 2 to Step 4 until $s = S$.

After S users are selected for $d \in \mathcal{D}$, each RRH calcuates the beam matrix selection metric using (7) and sends it to the F-AP. Subsequently, the F-AP chooses the reference beam matrix using (8).

IV. NUMERICAL RESULTS

In this section, we compare the sum rate performance of the proposed ODIA-BS and SE-ODIA-BS with the conventional schemes such as max-SNR, min-interfernece-to-noise ratio (INR), ODIA, and SE-ODIA [10].

Fig. 2 shows the sum rate of the SE-ODIA-BS versus η_I when $K = 3$, $M = 3$, $S = 2$, $L = 2$, $N = 40$, and $|\mathcal{D}| = 8$. If η_I is small, there are no eligible users who cannot satisfy the contraint (14), and then the lower sum rate can be achieved. On the contrary, when η_I is high, users who can interfere with other users can be selected. Therefore, the optimal η_I which maximizes the sum rate can be obtained as shown in Fig. 2. Since a higher SNR results in a larger interfernece to the users, the optimal η_I increases as the SNR increases. Note that the optimal η_I becomes 1 at high SNR regime for the SE-OIDA-BS scheme. Thus, we set $\eta_I = 1$ in the following simulations.

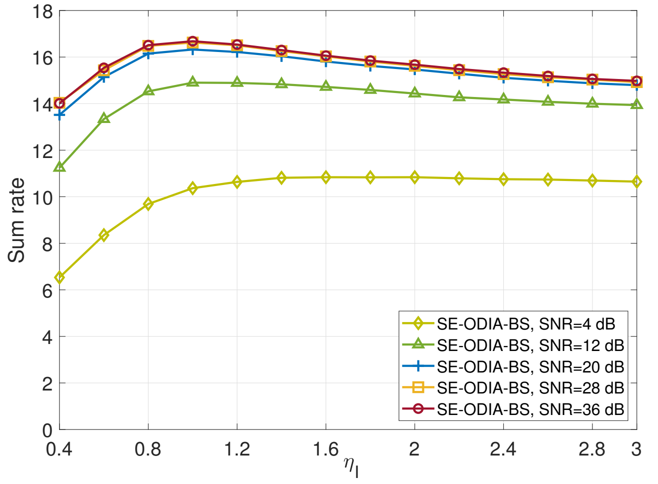

Fig. 2. Sum rate performance of the SE-ODIA-BS versus η_I, when $K = 3$, $M = 4$, $S = 2$, $L = 2$, $N = 40$, and $|\mathcal{D}| = 8$.

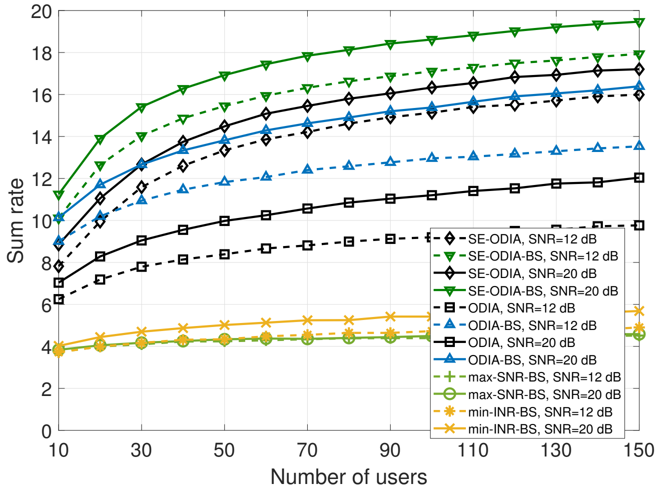

Fig. 3. Sum rate performance of each scheme versus N, when $K = 3$, $M = 4$, $S = 2$, $L = 2$, and $|\mathcal{D}| = 8$ for BS.

Fig. 3 illustrates the sum rate performance for varying N, when $K = 3$, $M = 4$, $S = 2$, $L = 2$, and $|\mathcal{D}| = 8$ for BS. In Fig. 3, the sum rate performance of the proposed schemes increases as N increases because of multi-user diversity gain. Compared to the max-SNR-BS and min-INR-BS schemes, which are beam selection aided max-SNR and min-INR, the ODIA-BS and SE-ODIA-BS schemes outperforms the other schemes. Furthermore, the result shows that the gain of beam selection is significantly larger in (SE-ODIA-BS) about four times than the conventional schemes. In addition, it can be shown that the ODIA-BS and SE-ODIA-BS achieve higher sum rate performance than ODIA and SE-ODIA, respectively.

Fig. 4 depicts the sum rate performance versus SNR, when $K = 3$, $M = 4$, $S = 2$, $L = 2$, and $|\mathcal{D}| = 8$ for BS.

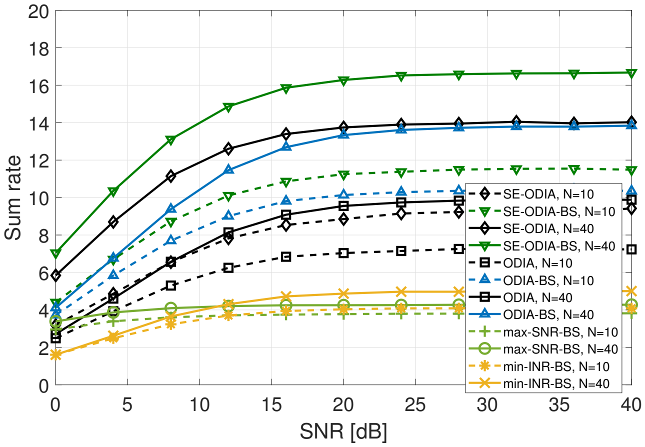

Fig. 4. Sum rate performance of each scheme versus SNR, when $K = 3$, $M = 4$, $S = 2$, $L = 2$, and $|\mathcal{D}| = 8$ for BS.

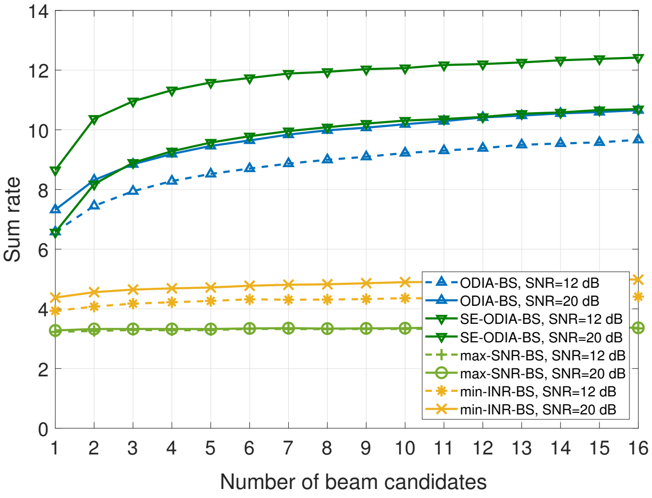

Fig. 5. Sum rate performance versus $|\mathcal{D}|$, where $K = 3$, $M = 4$, $S = 3$, $L = 2$, and $N = 40$.

The sum rate of the proposed schemes are saturated in the high SNR regime because the inter-cell interference cannot be zero for the fixed number of users in the cells. The sum rate performance of the proposed ODIA-BS and SE-ODIA-BS are higher than those of ODIA and SE-ODIA, respectively, especially in high SNR regime.

Fig. 5 illustrates the sum rate performance with varying $|\mathcal{D}|$ when $K = 3$, $M = 4$, $S = 3$, $L = 2$, and $N = 40$. As $|\mathcal{D}|$ increase, the sum rate of the proposed schemes are improved by diversity gain of reference beams. It is shown that the sum rate performance of the SE-ODIA-BS is higher than that of the ODIA-BS scheme in all $|\mathcal{D}|$ ranges, since users are selected in order to maximize the sum rate, where ZF filtering is used at the receiver in the SE-ODIA, whereas users who have the smallest interference are selected in ODIA. It is worth noting that the proposed ODIA and SE-ODIA schemes are more proper schemes to apply beam selection method since the conventional schemes, especially max-SNR-BS, cannot achieve a sufficient beam diversity gain along the increase in $|\mathcal{D}|$.

V. CONCLUSION

In this paper, we proposed two coordinated downlink interference alignment techniques for the fog radio access networks (F-RANs), in which each remote radio head (RRH) jointly generates multiple random beamforming matrices and users feed back their effective channel vector to the corresponding RRH. Based on the feedback, the fog access point (F-AP) selects the optimal beam matrix to maximize the sum-rate of the F-RAN. The sum-rate performance can be efficiently improved via the proposed techniques even when there exist a small number of users in each RRH, compared with the conventional schemes. Note that the proposed techniques operates with a low-signaling overhead on backhaul link. However, they linearly increase the feedback overhead from users to RRH according to the number of random beamforming matrices. There exist a trade-off between the sum-rate performance and feedback overhead, and we leave this as a further study.

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